

GPS constraints on Glacial Isostatic and Neotectonic Crustal Motion and Present-day Ice Sheet Mass Balance in Antarctica

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Precise GPS geodetic measurements in Antarctica measure glacial isostatic motion, in addition to tectonic strain. These geodetic measurements, currently being undertaken by several projects, are expected to provide important constraints on Antarctic deglaciation history and the viscosity structure of the mantle, if they are of sufficient accuracy and density. High quality GPS measurements are complementary to upcoming satellite measurements of surface height (IceSAT) and mass redistribution (GRACE), and will play an important role in constraining the pattern and magnitude of glacial isostatic adjustment, paving the way for accurate measurements of the present-day mass balance state of the Antarctic Ice Sheet. Further, these GPS measurements will provide a critical geodetic network for referencing future precise interferometric synthetic aperture radar (InSAR) measurements of ice and crustal dynamics. Pinning down the glacial isostatic signal in the crustal uplift data allows the pattern of neotectonic motion to be isolated, and the coupling between tectonic and glacial isostatic adjustments to be explored. The requirement for precision at the mm/yr rate level, as well as the need for ground truth points for satellite data, drives the need for continuous GPS measurements at strategic locations within a larger continent-wide geodetic network.

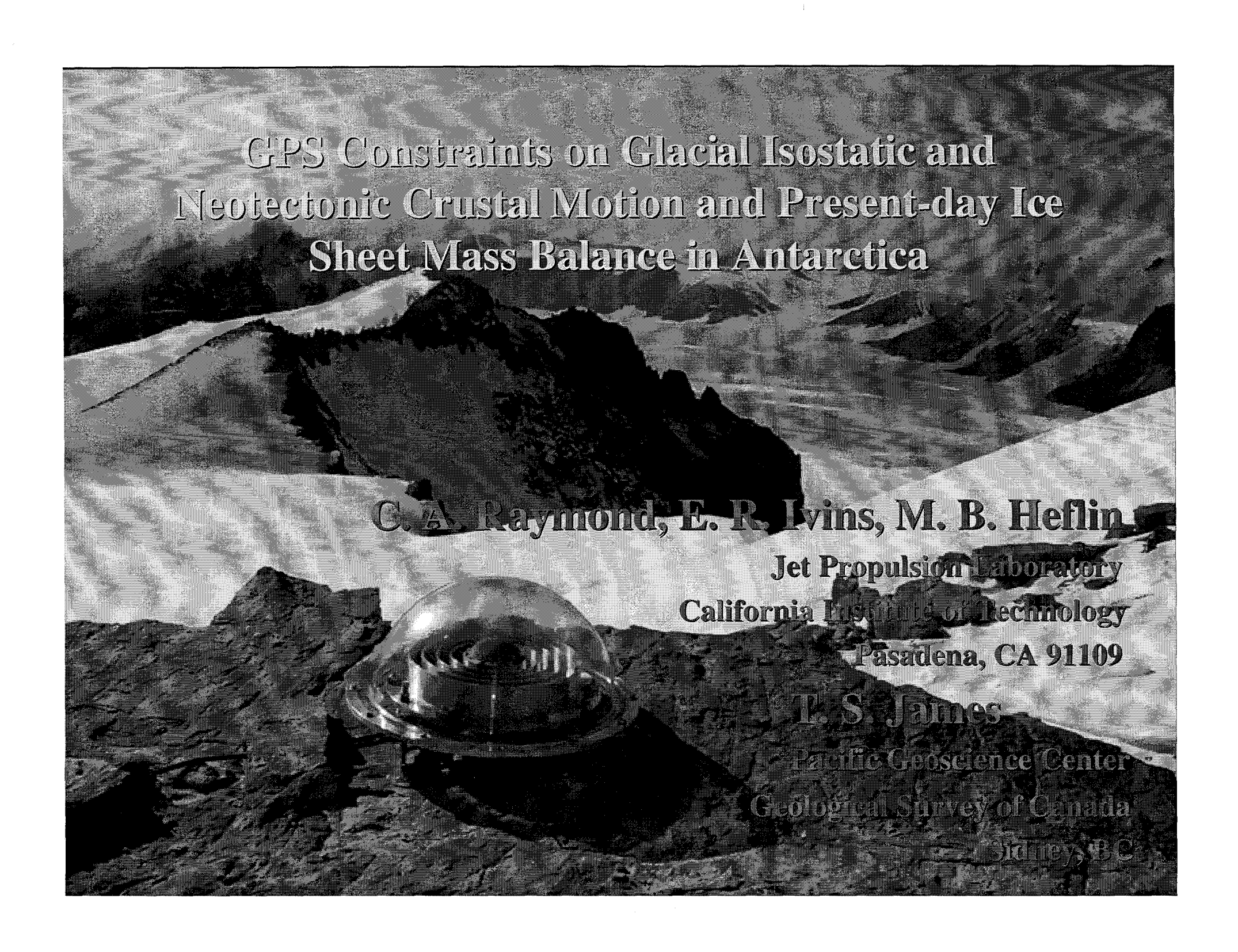
To address the glacial loading and neotectonic crustal deformation questions, data from bedrock sites throughout the continent are required. Data from the Transantarctic, Ellsworth and Whitmore Mountains are expected to yield significant constraints on the glacial loading history, as these areas are in proximity to the major ice domes. Competing scenarios for glacial load history in Antarctica result in differing predictions for patterns and magnitudes of crustal uplift (James and Ivins, 1998). Recent modeling exploring the sensitivity of glacial rebound to mantle viscosity and neoglaciation history raises the possibility that the memory of the Antarctic lithosphere may be most sensitive to ice mass changes on millennial time scales (Ivins et al., 2000). As such, the pattern of uplift may be more complex than predicted by previous models. The potential for complex viscoelastic response of the lithosphere to past ice mass changes invalidates the use of simple models to remove the glacial isostatic signal from the combined GRACE and GLAS (ICESat) measurements. Models utilizing precise GPS displacements, combined with seismological constraints on mantle viscosity structure, and accumulation data from ice cores, will refine the glacial loading history and its spatial variability.

Our autonomous GPS stations in the Dry Valleys and Royal Society Range (Mt. Coates [-77.8, 162.0] and Mt. Cocks [-77.5, 162.5]) have produced high quality time series over a four to five year span. A few days of useable data were collected during the 2000 austral winter, whereas all other data were obtained during sunlit periods. Vertical rate estimates have not yet emerged from the noise, but horizontal rates of motion from these and other permanent coastal sites suggest a more youthful isostatic rebound than predicted by unloading from Last Glacial Maximum alone. This inference implies a mantle viscosity below 10^{21} Pa-s and significant neoglaciation fluctuations. Future expansion of the network in the Transantarctic Mountains will provide robust constraints to test these ideas.

The remote bedrock environments required for GPS measurements pose significant challenges to obtaining the required high quality continuous data. Supplying station power through the austral winter is particularly challenging; however, much experience has been gained and recent progress has been made to maintain operations through the winter. Low-power smart systems utilizing the fewest number of moving parts are optimal for meeting the environmental challenges. Snow and ice accumulation is a significant problem, both in terms of the increased GPS signal error from accumulation on the antenna, and as a negative factor in power generation (snow covering solar panels and ice buildup on wind turbines). These problems can be mitigated through the judicious selection of sites and equipment.

REFERENCES

- Ivins, E. R., C. A. Raymond and T. S. James, 2000. The influence of 5000 year-old and younger glacial mass variability on present-day crustal rebound in the Antarctic Peninsula. *Earth, Planets and Space*, 52, 1023-1029.
- James, T.S. and E.R. Ivins, 1998. Predictions of Antarctic crustal motions driven by present-day ice sheet evolution and by isostatic memory of the Last Glacial Maximum, *J. Geophys. Res.*, 103, 4993-5017.

A black and white photograph of an Antarctic landscape. In the foreground, a large, smooth, dome-shaped ice feature sits on a rocky, uneven surface. The background shows a vast, flat expanse of ice and snow, with distant, low mountains visible under a cloudy sky.

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Summary

- Possible tectonic motions within Antarctic plate
- Plausible rebound within plate
- GPS autonomous stations
- Analysis of motion at IGS stations

<http://geodynamics.jpl.nasa.gov/antarctica>

Tectonic Setting of the Antarctic Plate

- **Extension across Bransfield Strait**
- **Possible extension across West Antarctic Rift**
 - **Cannot be many cm/yr unless compensated at another boundary such as Pacific-Australia (Pac-Ant-Aus circuit)**
 - **Slow-spreading at Southwest Indian Ridge contributes significant uncertainty to plate circuit estimates of E-W Antarctic motion**
- **Microplates?**
- **Vostok?**

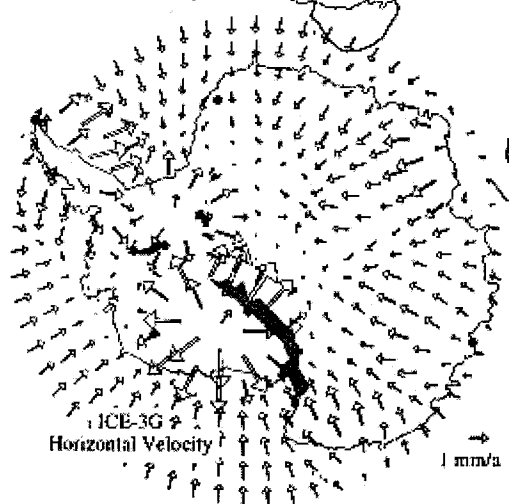
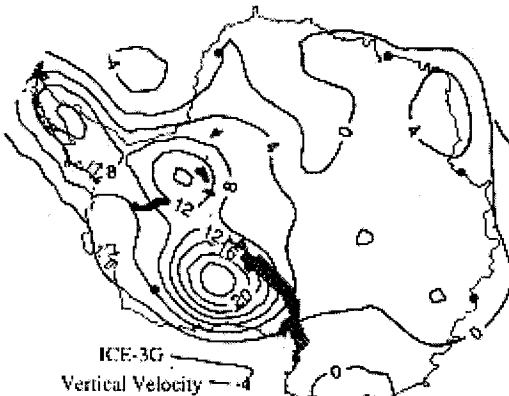
PREDICTED CRUSTAL MOTION FROM GLACIAL REBOUND

- Uplift of 1-2 cm/yr predicted in Ross Embayment and Ellsworth Mountains
- Various models have similar patterns, ICE-3G & D91 are end-members
- Present-day mass balance, and associated elastic rebound, predicted to be small with some exceptions

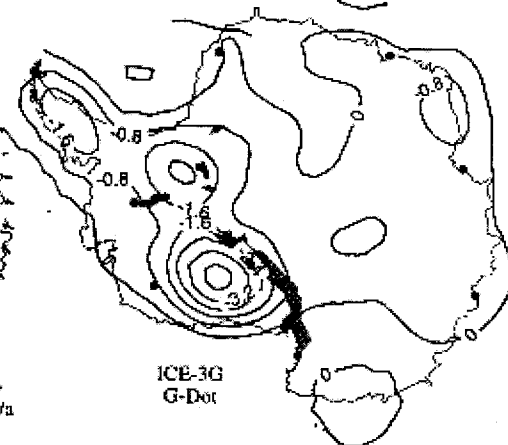
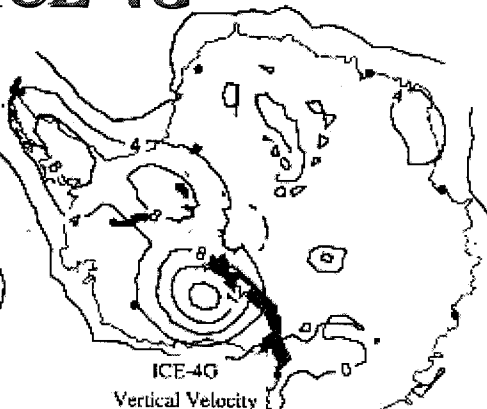
CAVEATS TO PREDICTIONS

- Mantle viscosity is key parameter controlling response of lithosphere to glacial loading and unloading
- Viscosities below 5×10^{20} Pa-s result in decreasing memory of LGM and enhanced sensitivity to Late Holocene history
- Constraints on viscosity and neoglacial history will reduce the ambiguity in the interpretation of crustal motion data

ICE-3G



ICE-4G



ICE-3G: Tushingham & Peltier, 1992

ICE-4G: Peltier, 1994

- ICE-3G: Large late melt component (7-4 Ka); 25 m of RSL rise
- Constrained by northern hemisphere ice sheet history & relative sea level curves
- Uses 10^{21} Pa-s upper mantle viscosity
- ICE-4G closer to CLIMAP reconstruction
- ICE-4G: ~25% lower predicted uplift rates
- James and Ivins, JGR, 1998

PREDICTED VERTICAL CRUSTAL MOTION (mm/yr)

James & Ivins, 1998

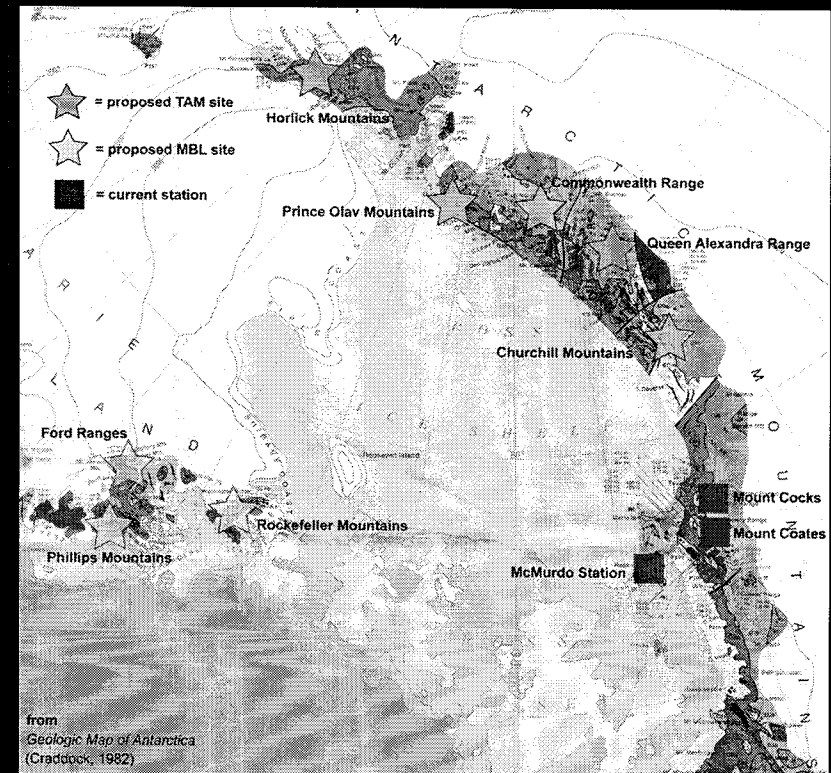
Site	LC79	ICE-3G	ICE-4G	D91
Syowa	0.7	0.8	1.6	1.1
Davis	2	2.7	2	1
Casey	4.3	2.8	1.9	3.4
Mt Melbourne	0.6	-2	-1	4.6
McMurdo	6.9	-0.1	0.2	3.7
Prince Olav Mtns	17.2	16.9	11.9	6.5
Exec. Comm. Range	3.7	4.4	4.2	7.6
Mt. Ulmer	2.1	4.4	2.5	12
Independence Hills	8.5	11.2	7.5	9.5
O'Higgins	6.7	3.6	4	-1.8
Dufek Massif	19.8	14.6	8.6	8.4
Basen	-0.1	-0.1	1	6.6

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Transantarctic Mountains

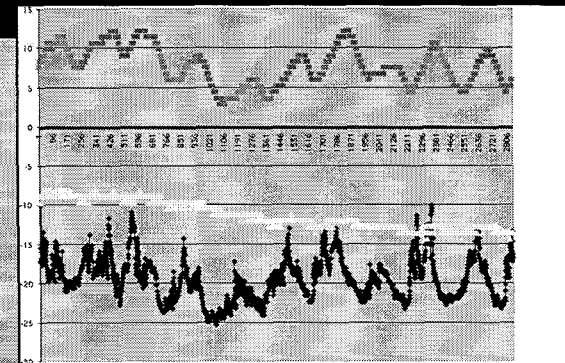
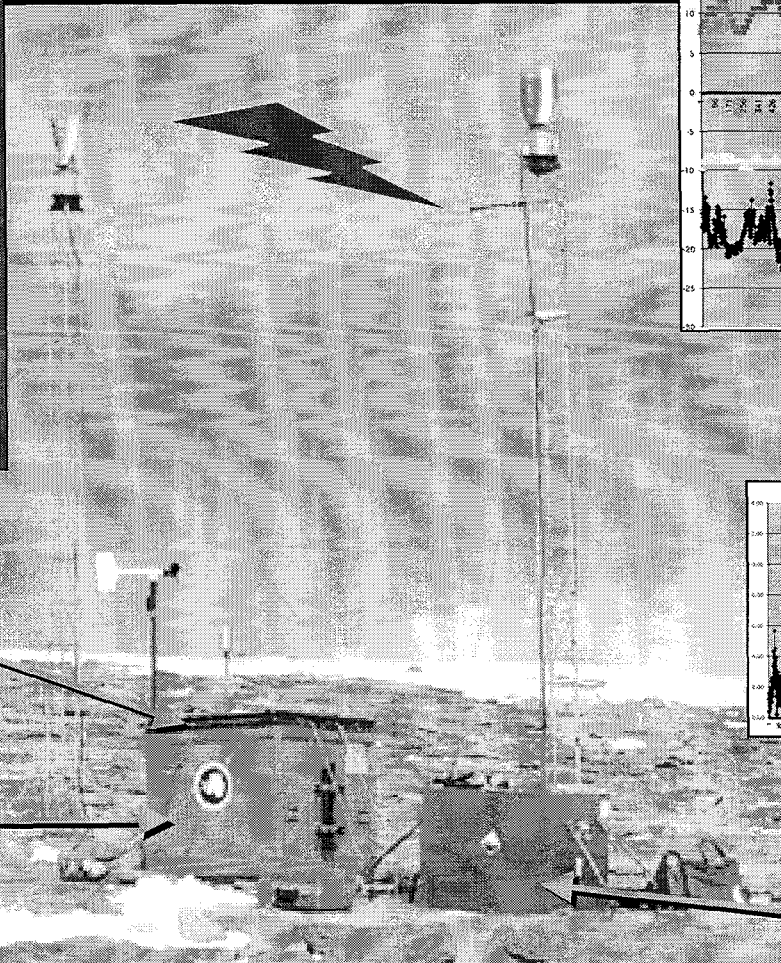
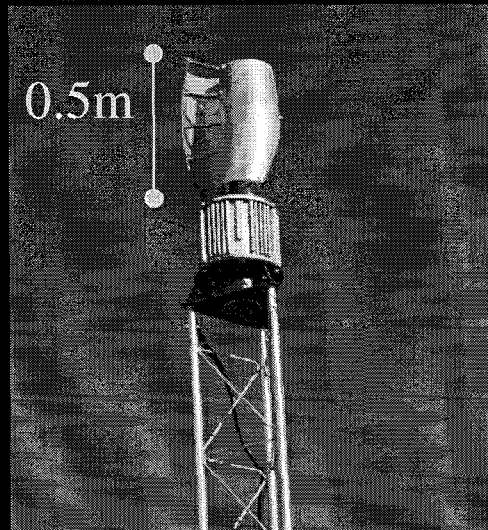
Autonomous GPS station locations



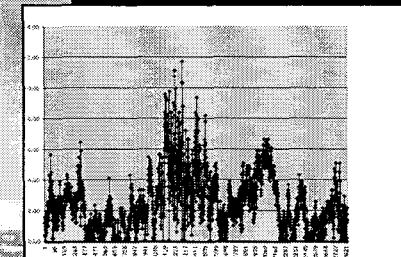
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Autonomous GPS Stations

Mt Coates



temperatures,
voltages and



wind speed,
direction

NiCd batteries

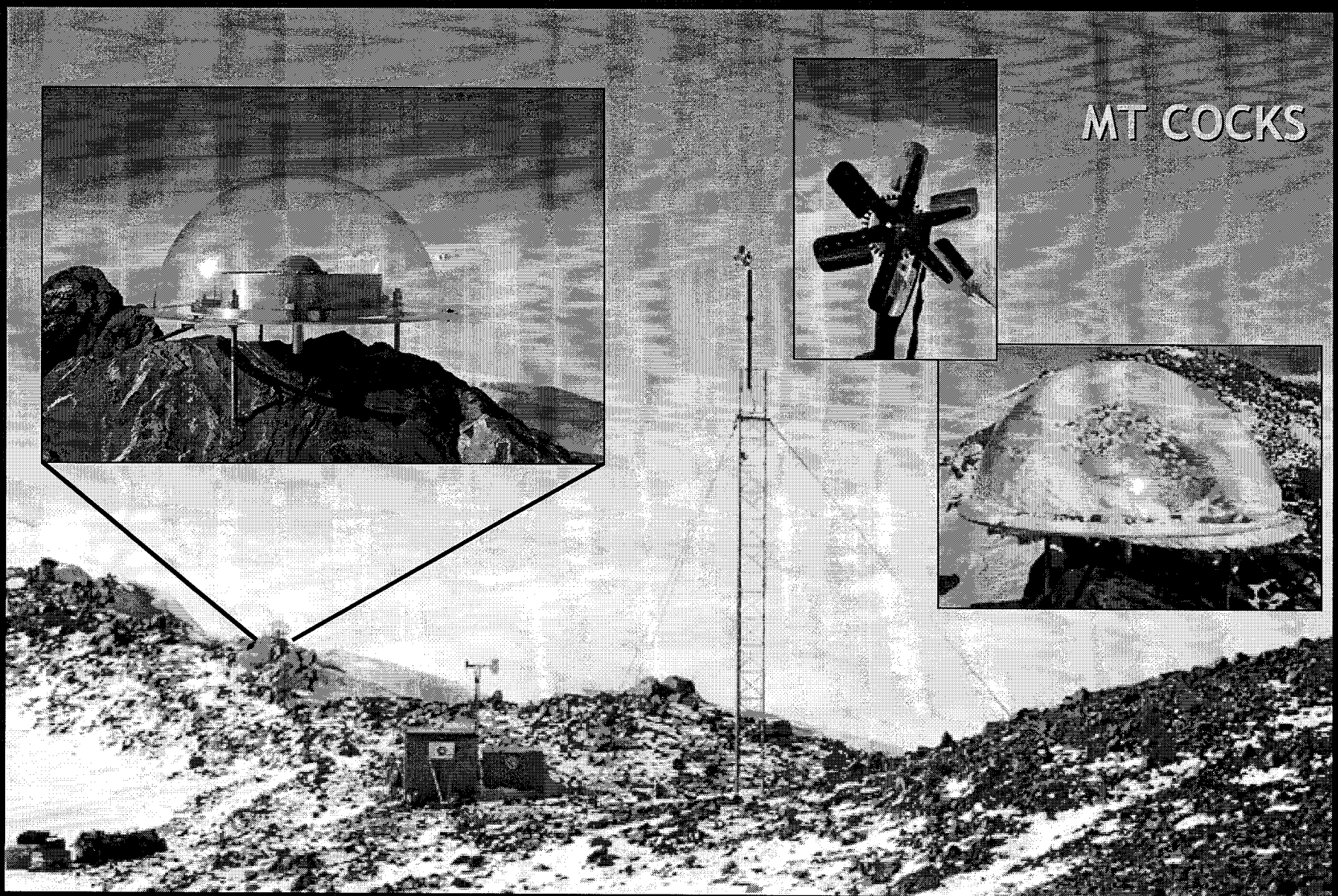
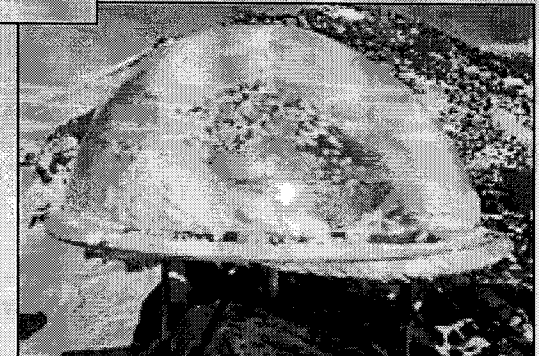
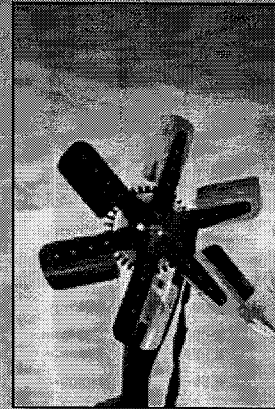
Solar Panels

Electronics

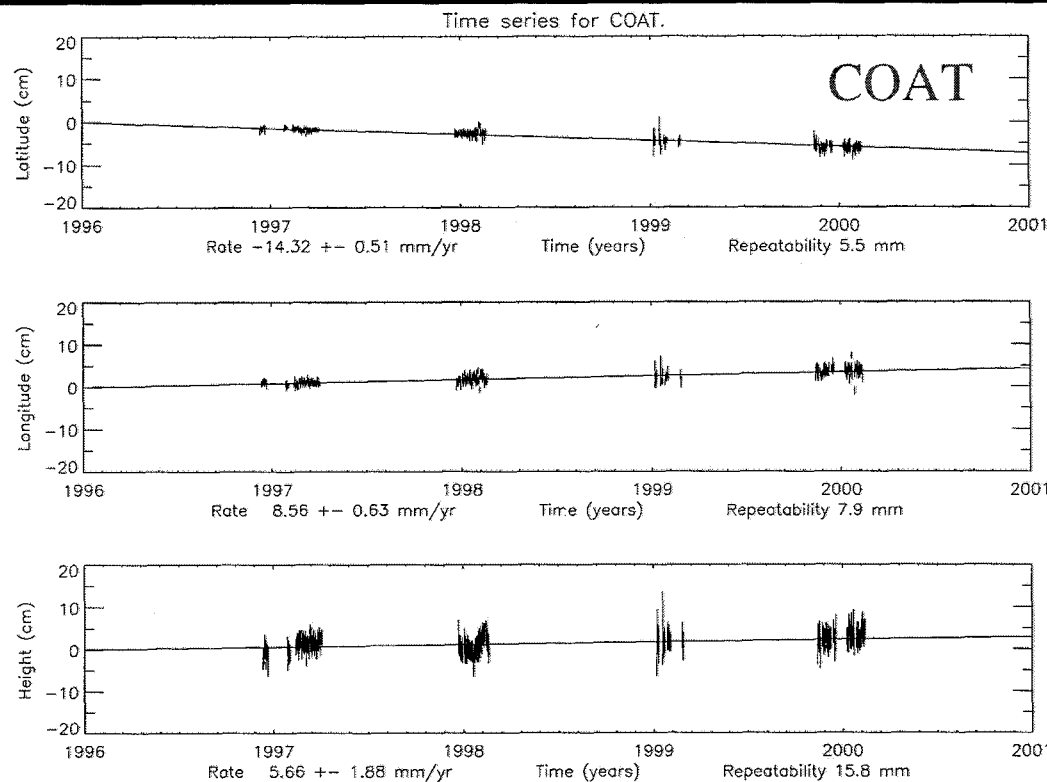
- Microcontroller
- RF Modem
- TurboRogue GPS Receiver

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MT COCKS



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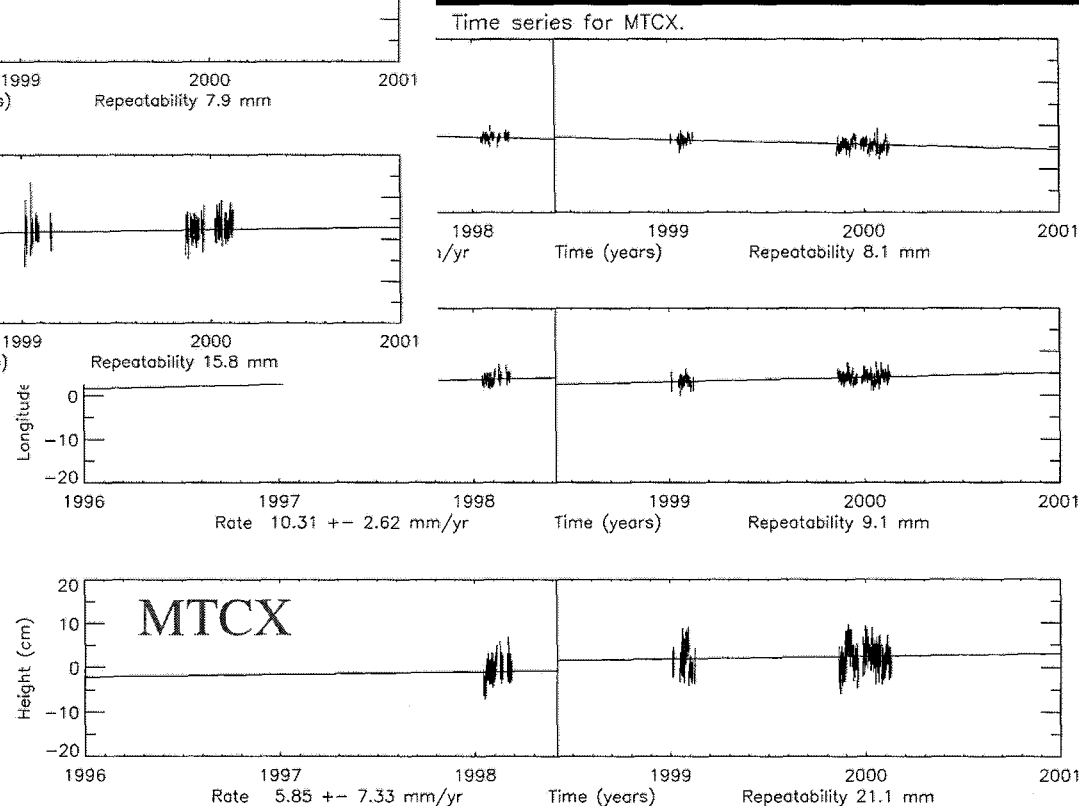


Mt Coates (COAT)

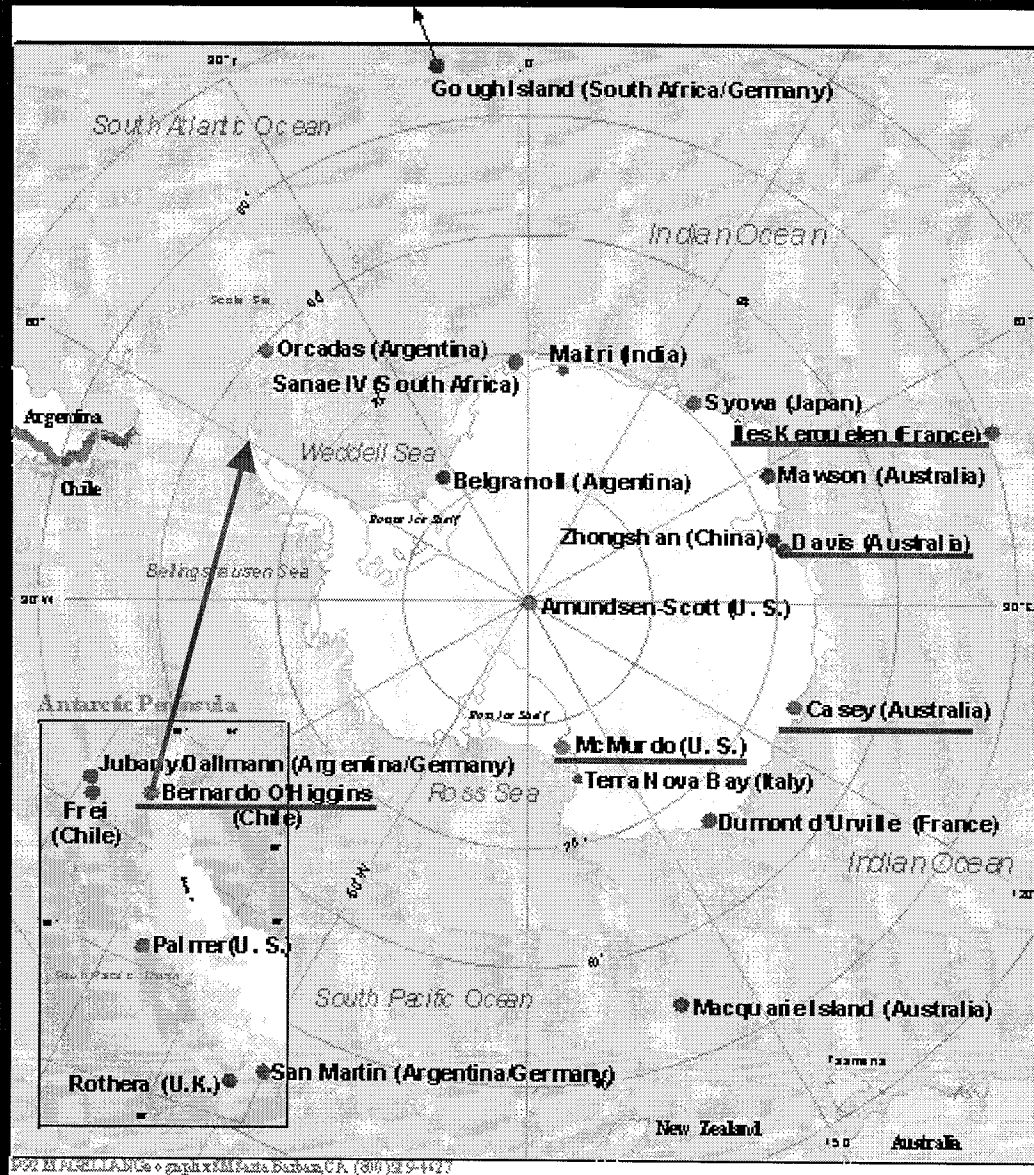
- Repeatabilities 5.5 (N), 7.9 (E), 15.5 mm (V)
- Four year seasonal time series

Mt Cocks (MTCX)

- Repeatabilities 8.1 (N), 9.1 (E), 21.1 mm (V)
- Three year seasonal time series with break



Geodetic Sites in Antarctica



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ANTARCTIC CRUSTAL MOTION FROM GPS

	North	East	Vert	Vert error
	mm/yr	mm/yr	mm/yr	mm/yr
CASEY	-11.68	3.94	8.63	2.7
DAVIS	-6.23	-1.95	2.61	2.7
MCMURDO	-11.85	10.96	1.99	3.0
O'HIGGINS	11.86	14.44	8.15	3.8
MT COATES	-14.32	8.56	5.66	5.5
MT COCKS	-11.07	10.31	5.85	7.5
KERGUELEN	-6.44	6.41	5.62	3.0

- Casey, O'Higgins and Kerguelen have significant uplift rates (Kerguelen is suspect)
- Horizontal rates are significantly different than NNR-Nuvel 1A

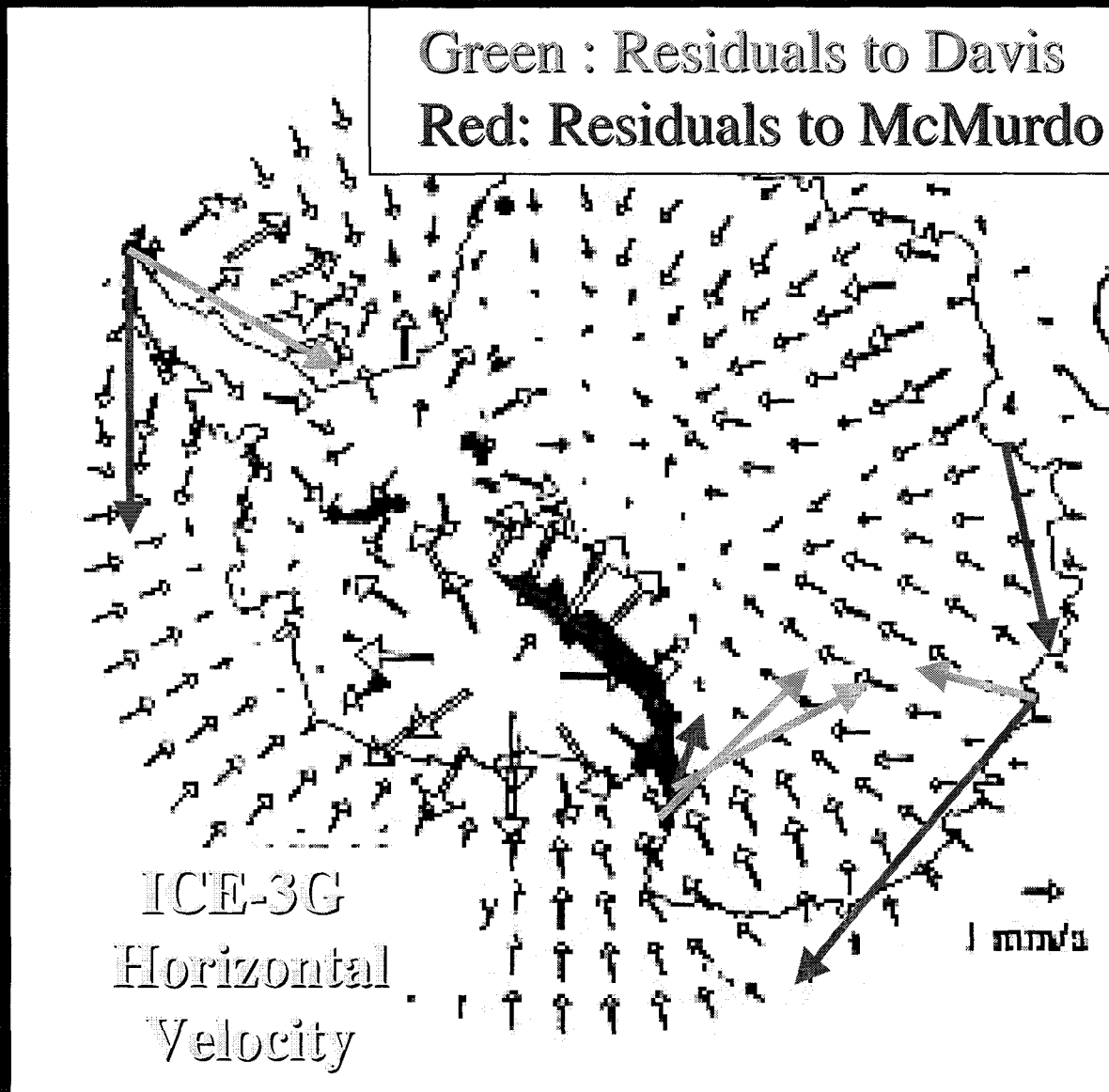
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James & Ivins, 1998

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All vectors relative to NNR Nuvel 1a



- Horizontal rates of several mm/yr predicted across West Antarctic Rift and towards Weddell Sea
- Predicted motion elsewhere generally towards center in Ross Embayment
- Observed velocities relative to Davis are more consistent with prediction
- Preliminary!

APPROACH TO MEASURING ICE SHEET MASS BALANCE & DERIVING TECTONIC MOTION

- **Gravity Recovery and Atmospheric Change Experiment (GRACE) will measure mass redistribution at long wavelengths (>700 km)**
- **Geoscience Laser Altimeter System (GLAS) on ICESat will measure surface accumulation to 1.5 cm accuracy in 100x100 km bins every 180 days**
- **Coordinated, strategically located GPS measurements will provide geodetic constraints on present and past ice sheet mass balance**
- **Interferometric Synthetic Aperture Radar (InSAR) will measure glacier mass balance, grounding line retreat, and crustal motion**
- **Correlative satellite and ground measurements will define present-day mass balance, post-glacial rebound and tectonic motion**
- **Improved seismological and ice core (accumulation history) data will further constrain past ice sheet history**
- **Dense autonomous ground stations (seismic, GPS, gravity) will enable this vision**

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